Technology Requirements for Small-Angular-Scale CMB Science

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New Detection Technologies for Discovery Workshop*

Arlington, TX

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*Organized by the Coordinating Panel for Advanced Detectors (CPAD) of the Division of Particles and Fields (DPF) of the American Physical Society (APS)

Technology Requirements Traceability from Science Goals

Outline of talk:

- Science goals
- The need for high-res CMB
- Signatures sought
- Systematics-busting technologies

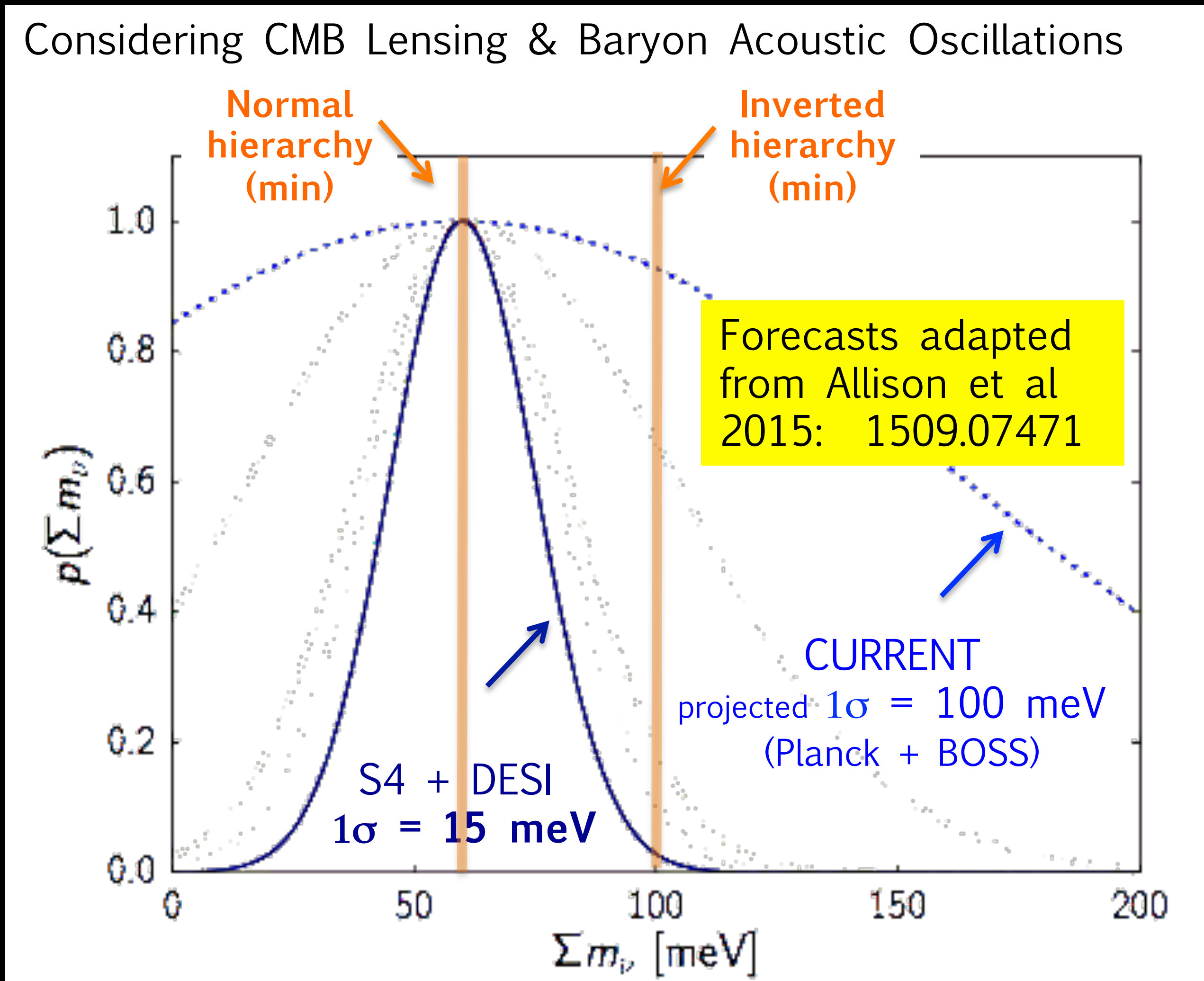
traceability

Physics & Cosmology from the CMB at Small Scales

- NEUTRINO MASSES (summed)
- # of EARLY RELATIVISTIC SPECIES
- INFLATION (delensing for r)
- DARK ENERGY
- MODIFIED GRAVITY
- EXOTICA (DM decay, strings, changing constants ++)

LARGE ANGULAR SCALES: SNAPSHOT OF EARLY UNIVERSE
SMALLER SCALES: + SECONDARY EFFECTS FROM THE LATE UNIVERSE

Neutrino Mass: S4 Goals



S4 goal: 4σ for minimum Σm_ν ($\Sigma m_\nu \sim$ 60 meV)
arXiv: 1309.5383

CURRENT 2σ:
$\Sigma m_\nu <$ 230 meV
Planck + BOSS
arXiv:1502.01589

Fisher errors; multipole cut in lieu of foreground subtraction

Primordial vs Late-time

Comparing the primordial universe (via the CMB) to the late-time universe as probed through baryons.

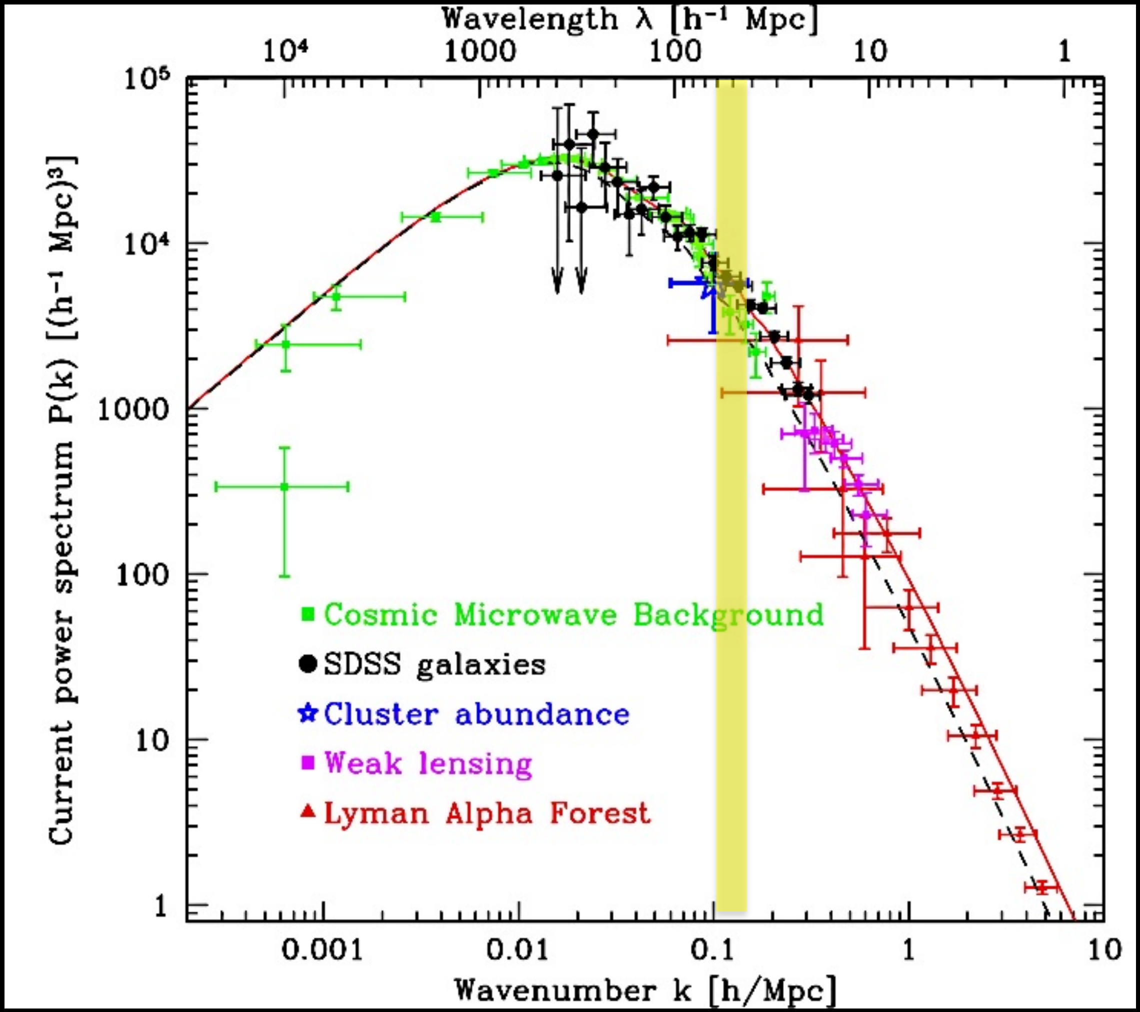


Figure from Tegmark 2005 (better data exist now!)

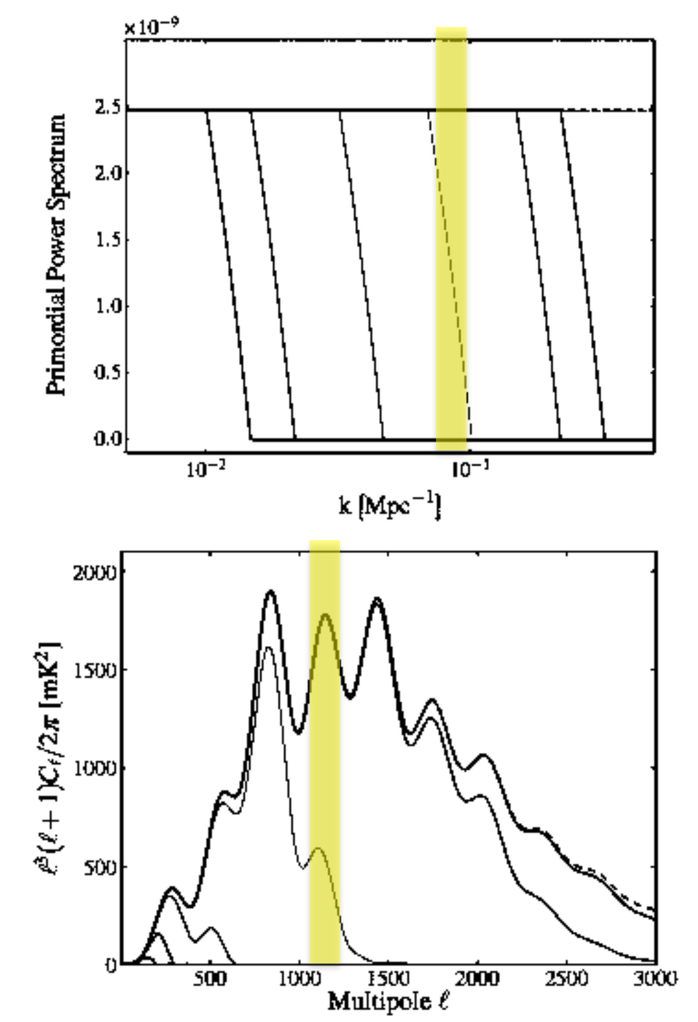
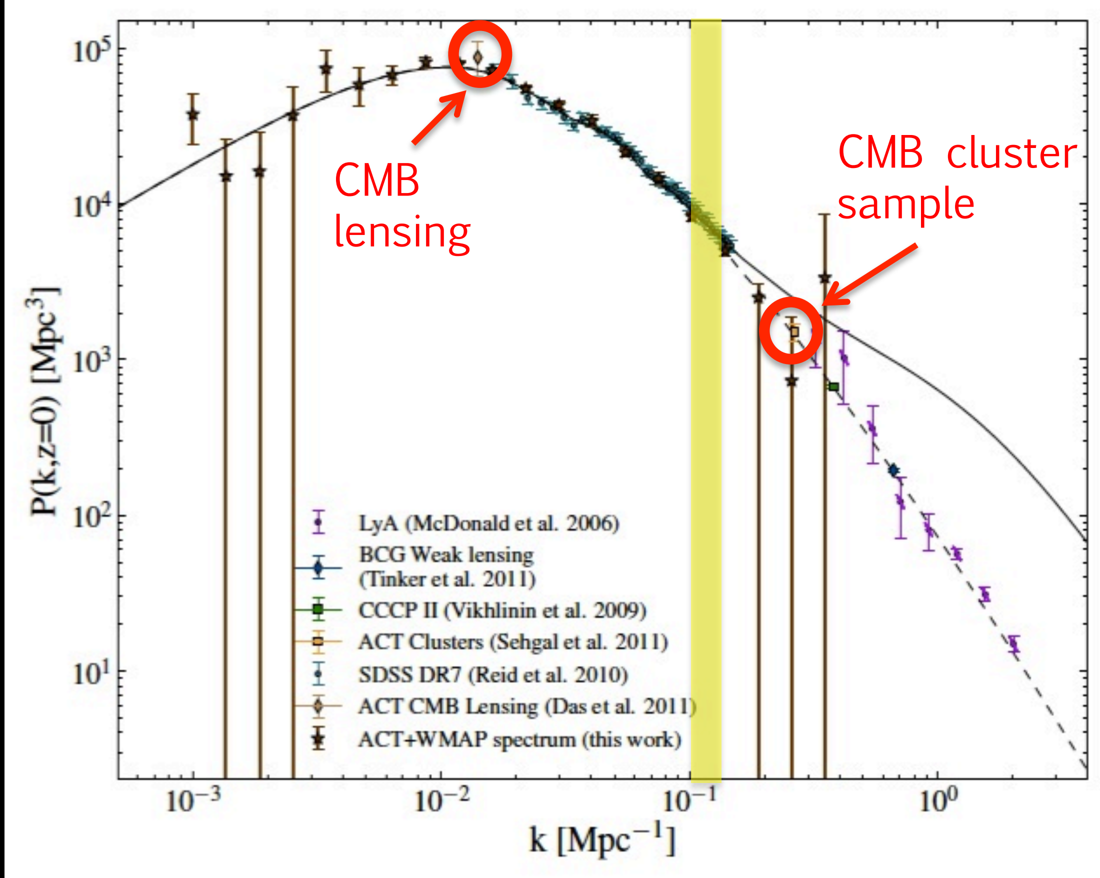


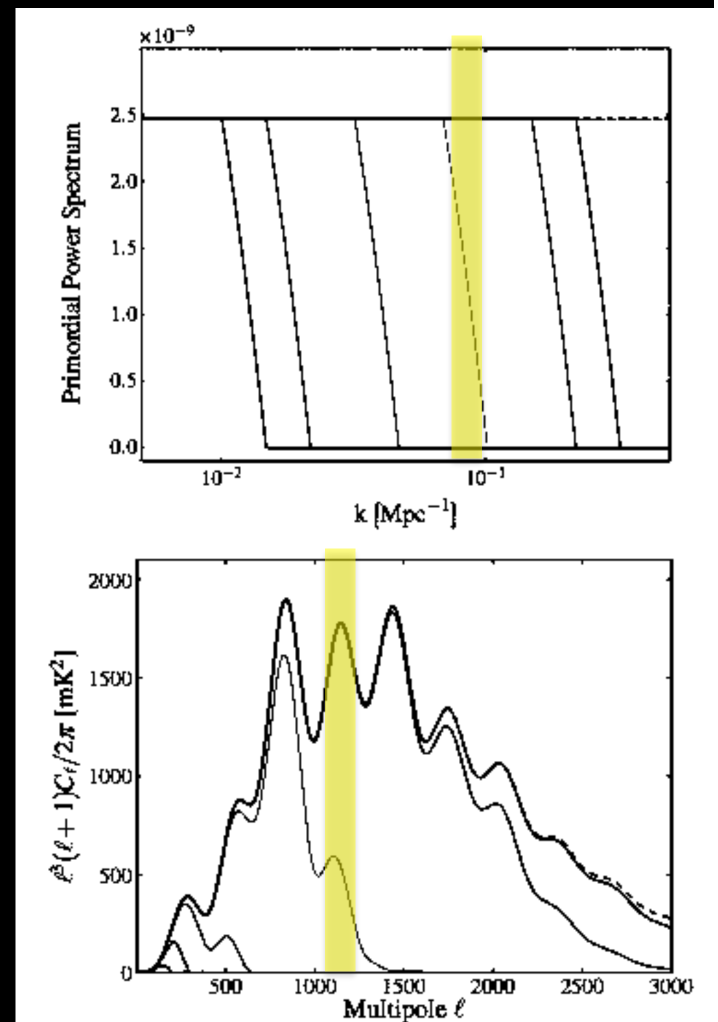
Figure from Hlozek et al 2011

The Need for Hi-res CMB

At small angular scales the CMB encodes late-time properties as well as primordial ones!

EXAMPLE PLOT (circa 2011)





Figures from Hlozek et al 2011 (so not all current data!)

The need for hi-res CMB

Neutrinos start out relativistic, wander out of small-scale potential wells, and then cool down, suppressing small-scale structure: need to compare large and small scales!

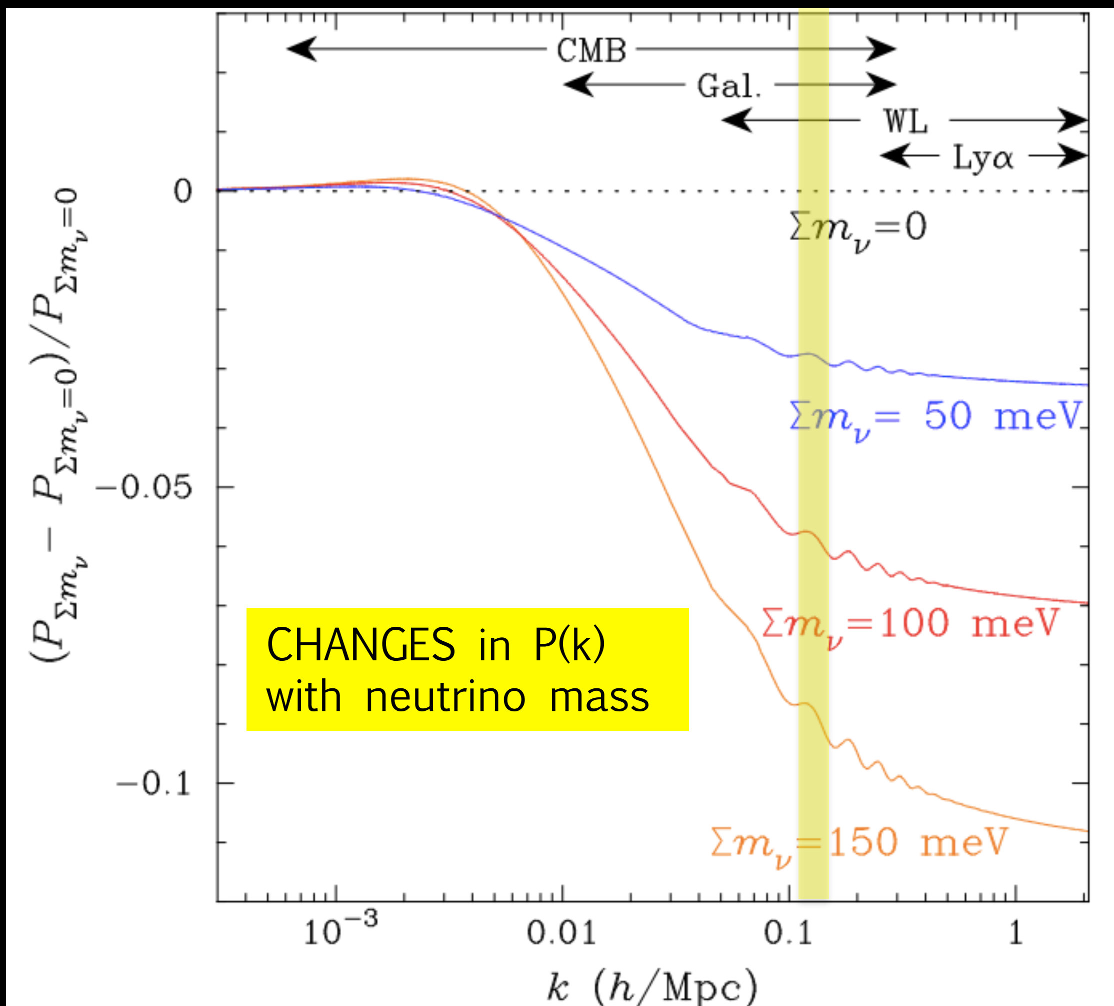
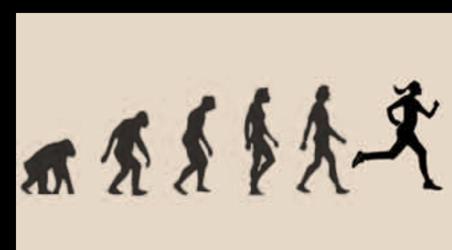


Figure from Snowmass White Paper: arXiv:1309.5383

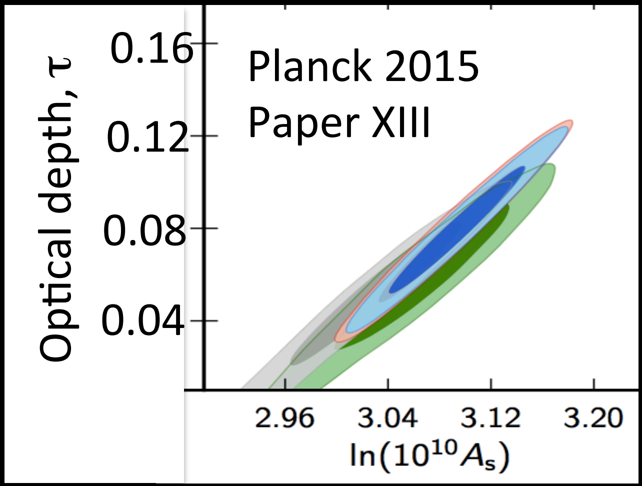
EVOLUTION:
Neutrinos and dark energy affect the expansion history of the universe, and the growth rate of structure.



Kahn talk: growth provides cosmic clock

… & the need for low-res CMB

NOTE: So Σm_ν depends on normalization at large angular scales, but the CMB power normalization A_s is difficult to detangle from the optical depth to reionization τ.



Accurate large angular scale polarization measurements break the degeneracy.

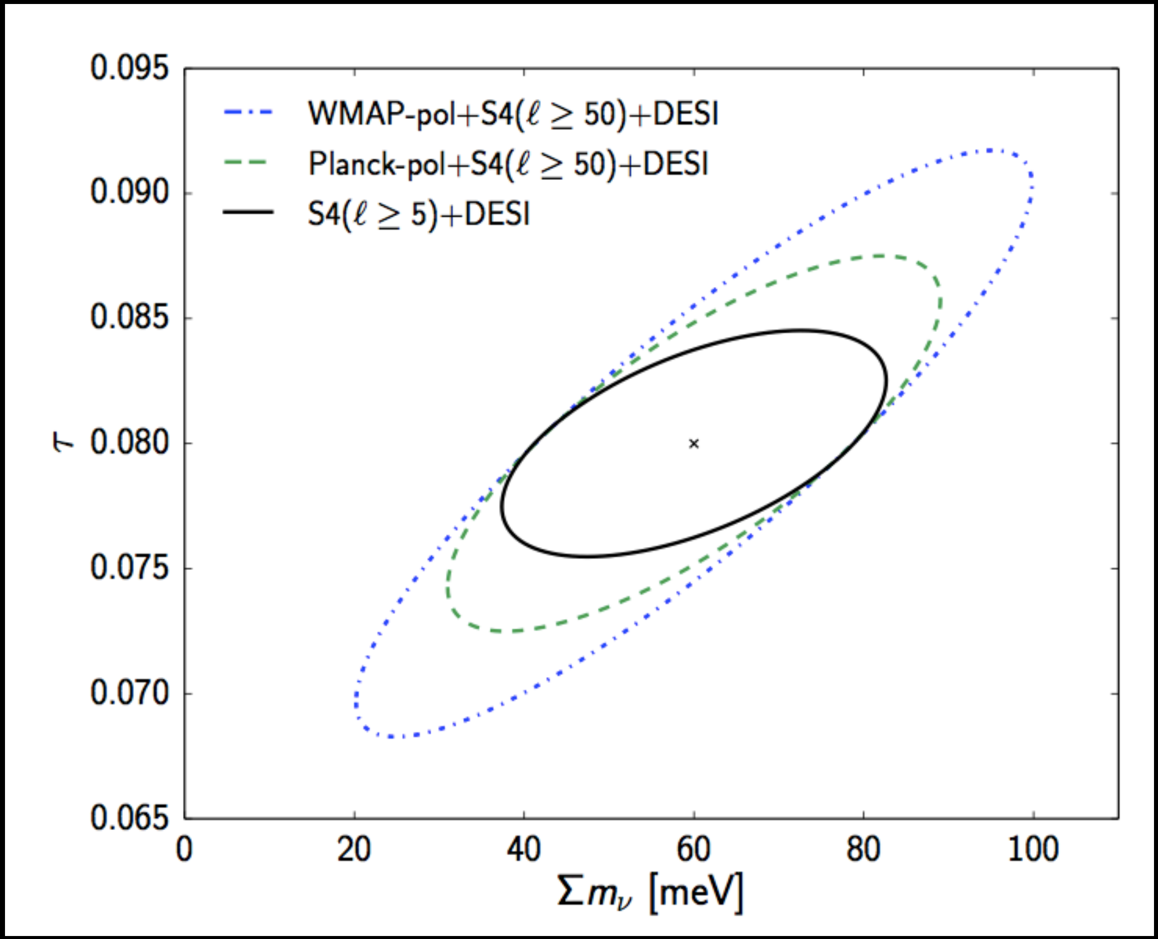
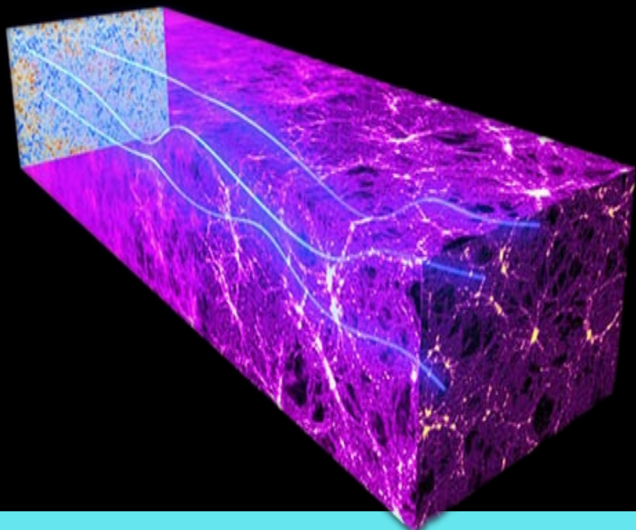


Figure from Allison et al, 2015: arXiv:1509.07471

Signatures Sought in the CMB

- GRAVITATIONAL LENSING OF THE CMB (map signature)
- CMB POWER SPECTRA (temperature & polarization)
- THERMAL SUNYAEV ZEL'DOVICH EFFECT (frequency signature)
- KINETIC SUNYAEV ZEL'DOVICH EFFECT (correlations with mass tracers)

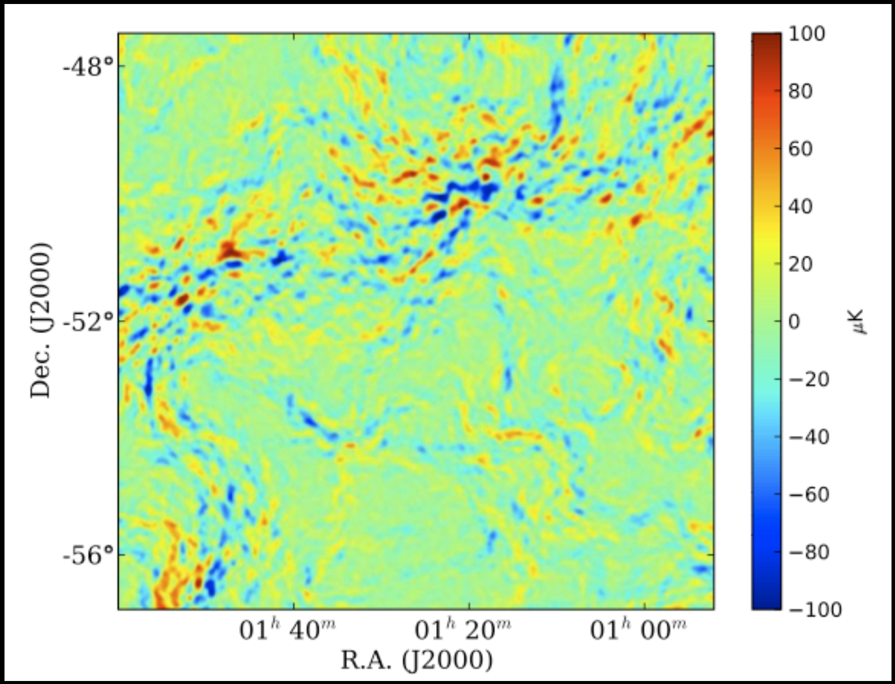
CMB Lensing from Map Signature



CMB lensing depends on all the mass from here to the CMB.

Structure is forming from gravitational collapse as the CMB traverses it.

Simulated difference between lensed and unlensed CMB in 10°x10° patch

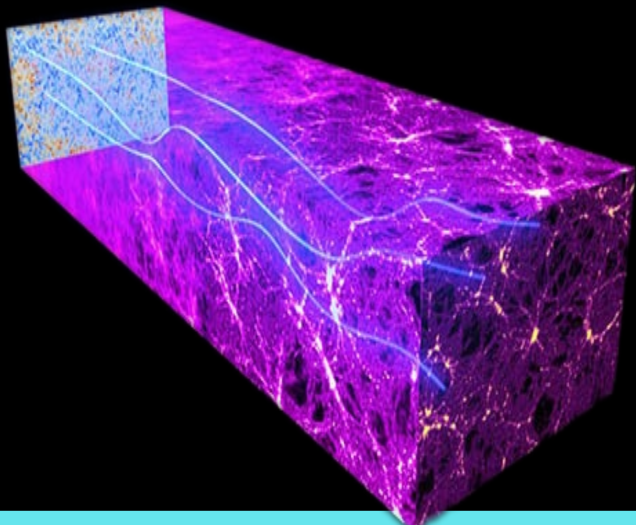


Large & small scales are coupled.

RULE OF 2-3: Typically ~ fifty 2-3' deflections, coherent over 2-3°, mainly coming from redshifts of 2-3.

Das et al, 2011, 1103.2124 (PRL 107, 021301.)

CMB Lensing Gains from Polarization



CMB lensing depends on all the mass from here to the CMB.

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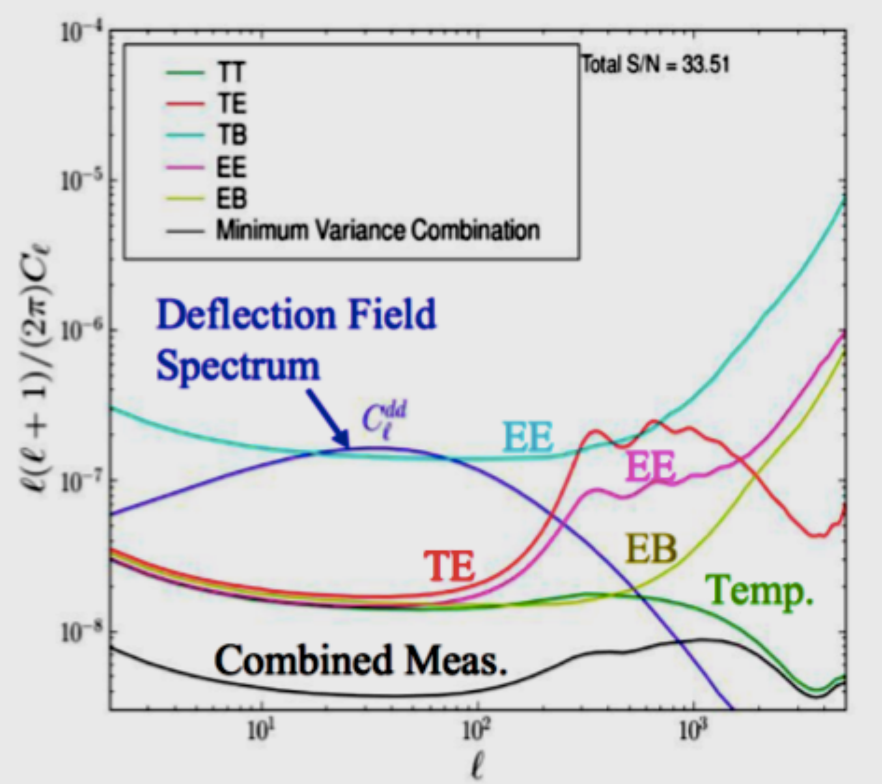
Example of Sensitivity Gains



DELENSING: recover and remove the modes correlated by lensing which serve as noise to the recovery of large angular scale B modes

Signatures Sought in the CMB

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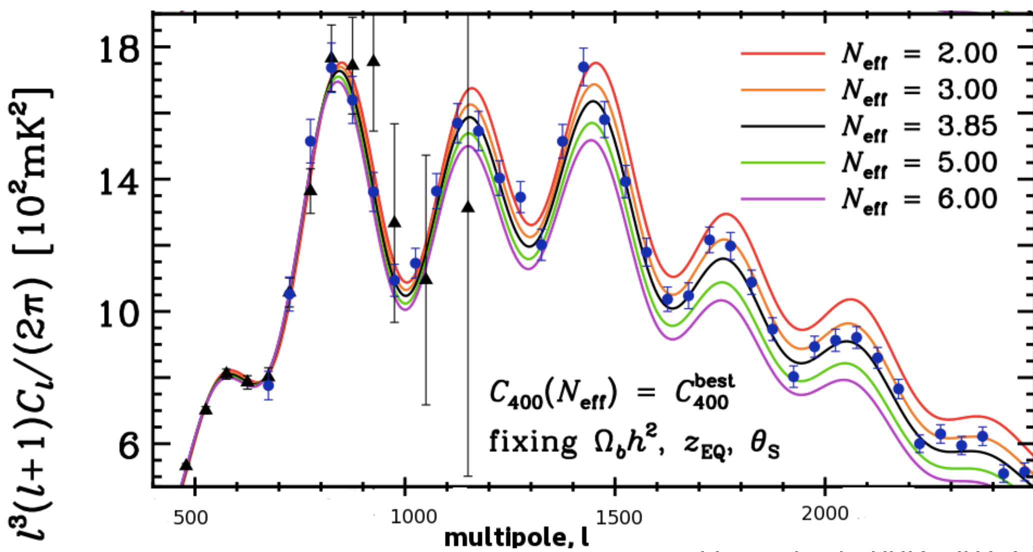
traceability

CMB POWER SPECTRA

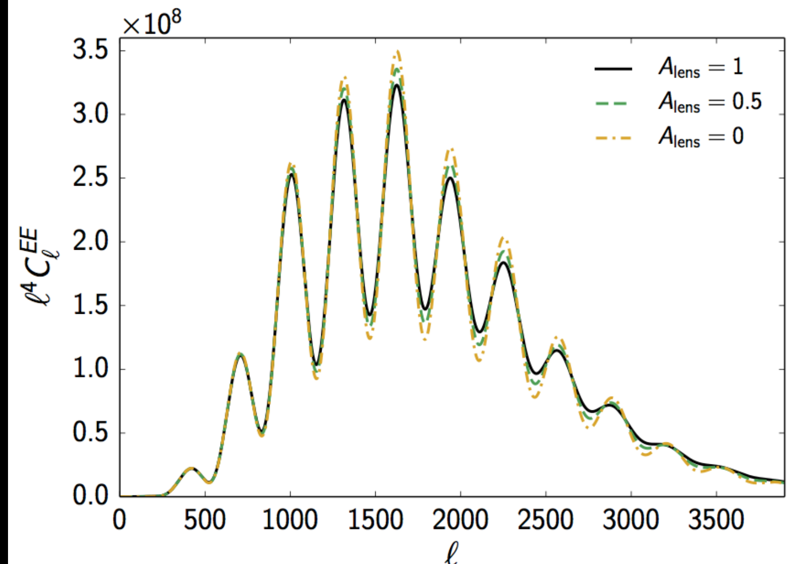
EXAMPLE: # Relativistic Species & TT Spectrum



Hou et al, PRD 2012

COMPARE TO:
N_{eff} = 3.12 +/- 0.32
Planck 2015 Paper XIII;
Planck + lowP
S4 GOAL: σ_N = 0.02

EXAMPLE: Lensing & EE Spectrum



Also: REIONIZATION FROM LOW ℓ POLZN SPECTRA

COMPARE TO:
A_L = 1.22 +/- 0.10
Planck 2015 Paper XIII;
Planck + lowP

Signatures Sought in the CMB

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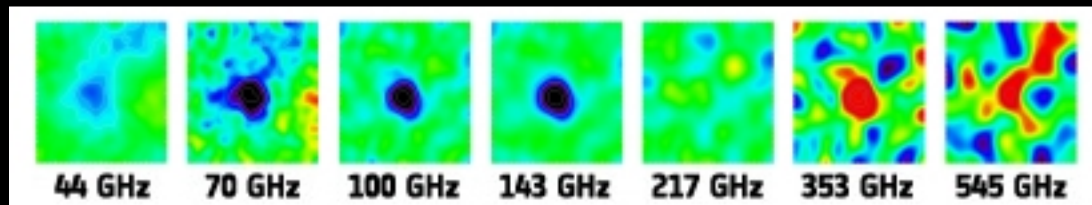
- KINETIC SUNYAEV ZEL'DOVICH EFFECT (correlations with mass tracers)

traceability

CMB Cluster Finding

CMB photons are Compton-up-scattered by hot gas in clusters: spoils their blackbody spectra

PLANCK CLUSTER



EXAMPLE PLOT: CLUSTERS AU NATUREL

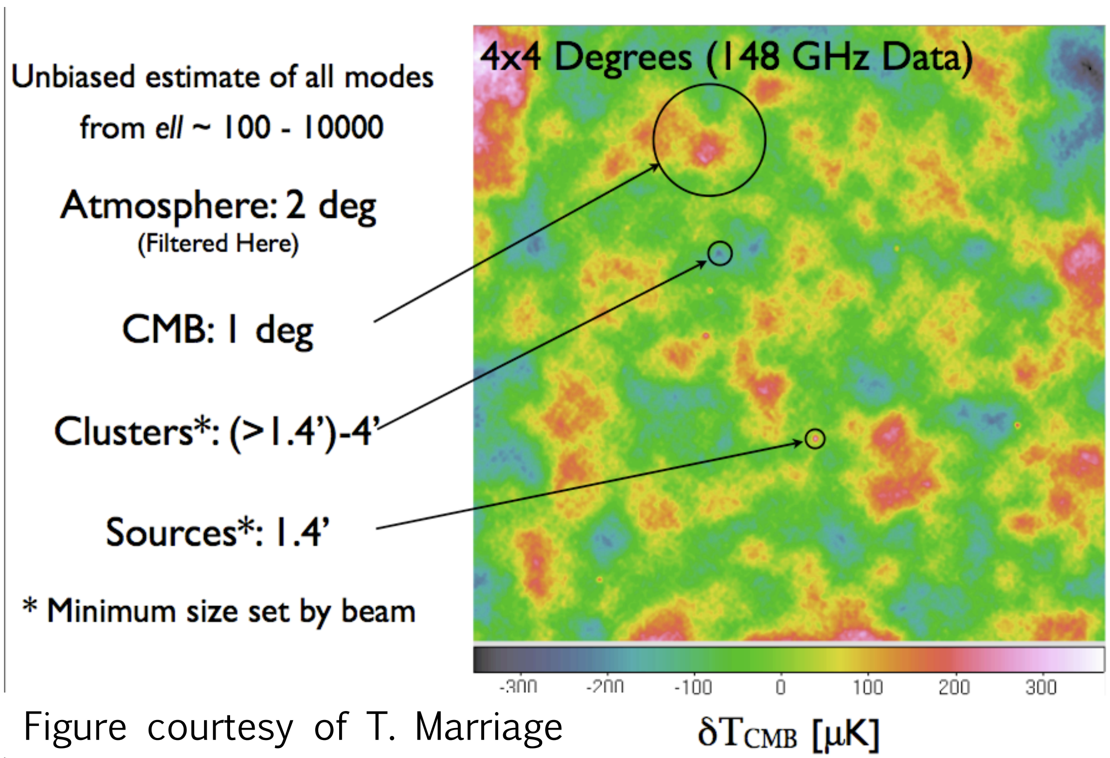


Figure courtesy of T. Marriage

COSMOLOGY from N(m,z):

- High resolution & sensitivity improve mass threshold;
- Large area improves N;
- Multi-frequencies prevent source contamination
- Need z! (optical surveys)
- Need m!

Signatures Sought in the CMB

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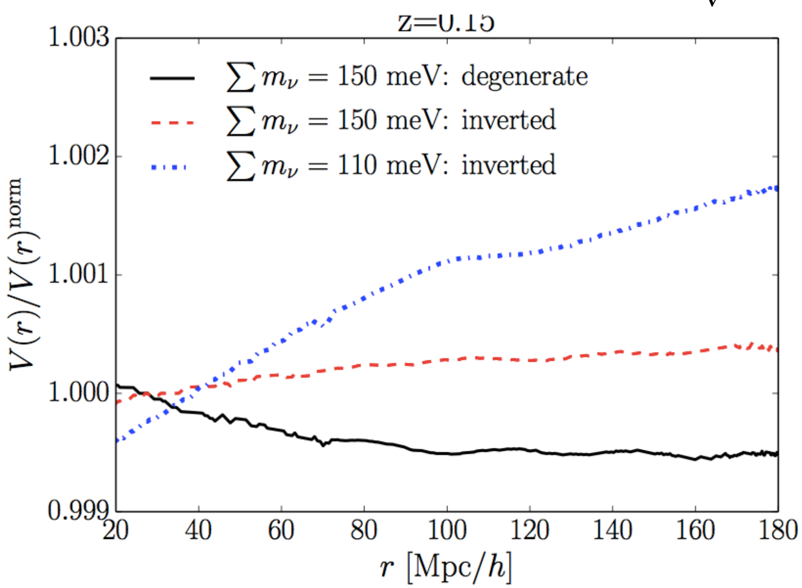
PAIRWISE VELOCITIES & Σm_ν



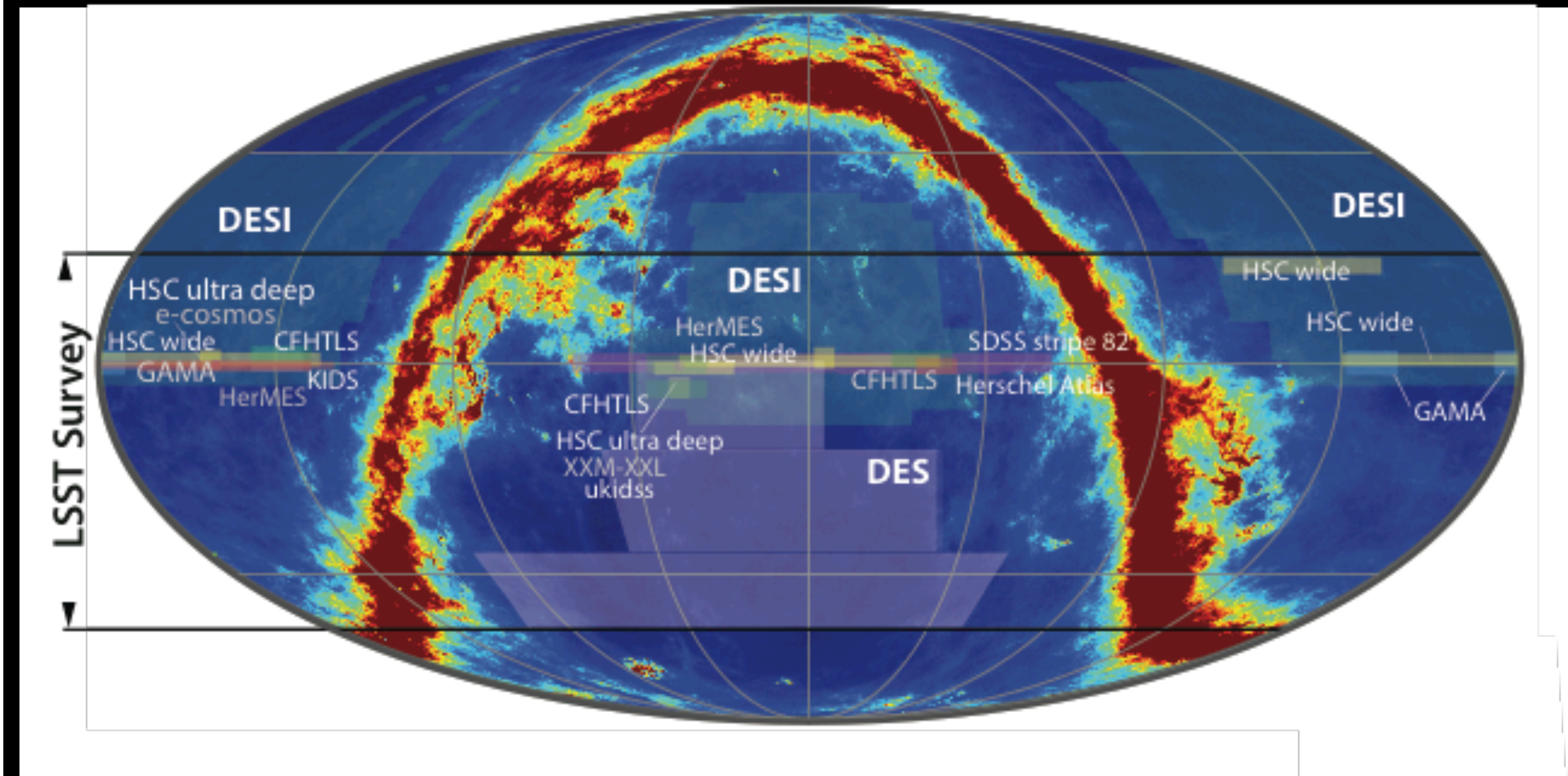
Mueller et al, PRD 2015

CMB photons are Doppler shifted from hot gas in moving clusters → another way to probe the growth rate of structure – large scale flows.

Requires mass tracers (optical surveys).

Overlap with optical surveys is key

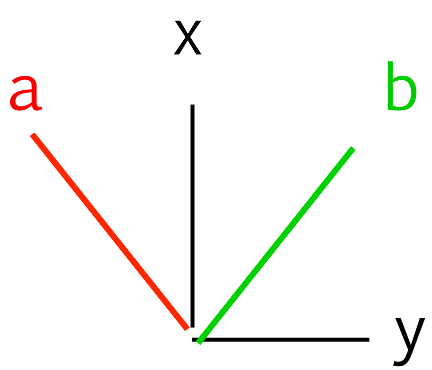
Foreground + optical survey coverage map



- Lensing – more info vs redshift with Lensing x Lensing tomography
- Cluster N(m,z) – need good masses and redshifts
- kSZ – need mass tracers

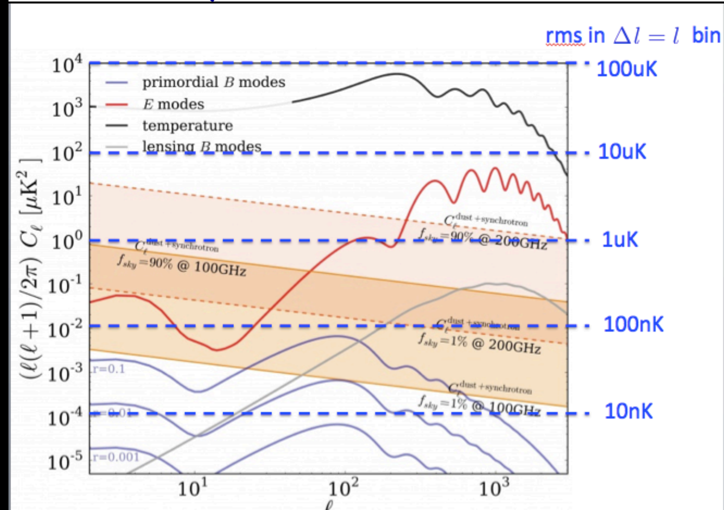
Systematics-busting Technologies

- As Ruhl & Arnold noted: high sensitivity & multiple frequencies of operation
- As Ruhl noted: modulation to suppress the atmosphere at large scales
- Also needed: good suppression of polarization systematics.



STOKES:
I = intensity
$Q = |E_x|^2 - |E_y|^2$
$U = |E_a|^2 - |E_b|^2$
V= circular

Recall from Ruhl's talk:
Q/U are small!

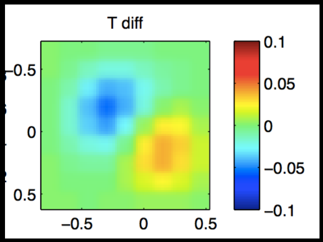


Errard, Feeny, Peiris, and Jaffe, arXiv:1509.06770

Polarization Systematics

- I → Q/U on-axis,
  RELEVANT I: T_{sky}~10 K (averages down if modulate faster than 1/f knee)

- I → Q/U near on-axis: dipole, etc.
  RELEVANT I: δT_{CMB} ~ 100 μK (pervasive)

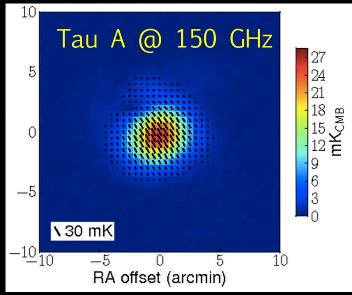


Example from BICEP2 (arXiv:1502.00596

- I → Q/U far side-lobes.
  RELEVANT I: Ground ~ 300 K (sky rotation at mid-latitude site helps)
  RELEVANT I: Galaxy ~ 1 mK, colored (pervasive)
  RELEVANT I: Sun ~ 5000 K, moon ~ 250 K (known position, rotation)

- Q ←> U (determining detector angles)
  REQUIRED: good method (man-made source?)
  REQUIRED: stability, good bandpass knowledge if frequency-dependent

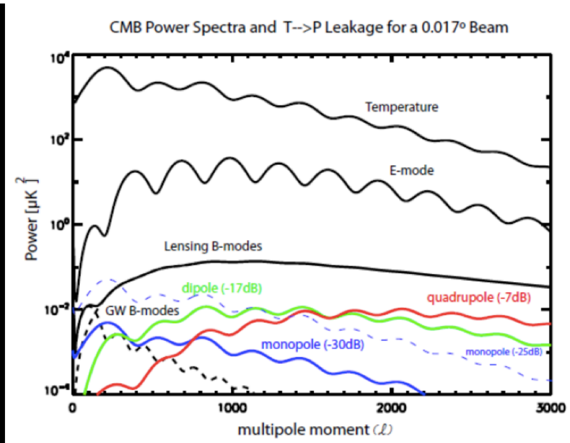
- Q/U emission from instrument itself
  IMPACT: mostly on sensitivity
  CONCERN: if scan-synch and/or diurnal



Astrophysical pol sources are messy! PB Collaboration, ApJ 794:2, 2014.

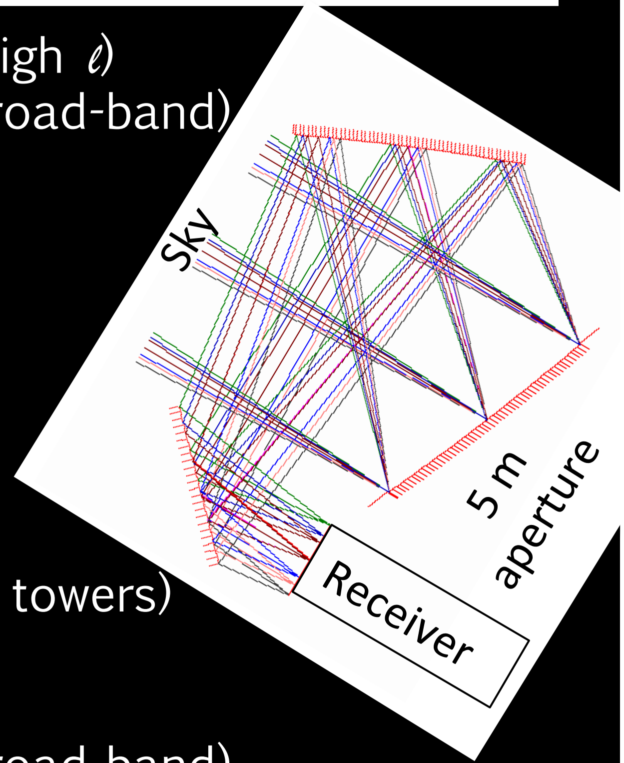
Polarization Systematics

- I → Q/U on-axis,
  TECHNOLOGY: modulators



Austermann et al, SPIE 2012

- I → Q/U near on-axis: dipole, etc.
  TECHNOLOGY: big, telescope (pushes effects to high ℓ)
  TECHNOLOGY: lenses to maximize fp (large & broad-band)



- I → Q/U far side-lobes.
  TECHNOLOGY: mirrors (control or eliminate gaps)
  TECHNOLOGY: baffling

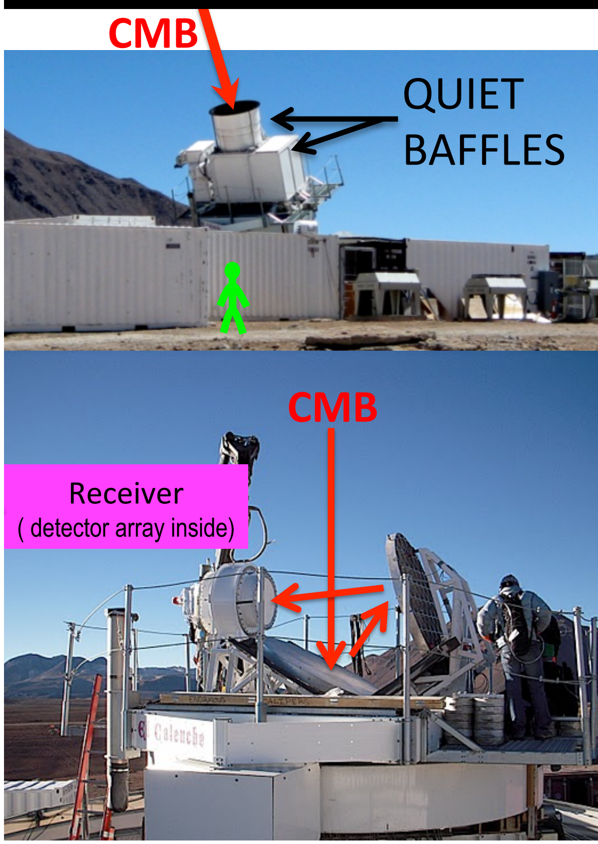
- Q <-> U (determining detector angles)
  TECHNOLOGY:innovative near-field methods
  TECHNOLOGY: far-field source (balloons, satellites, towers)

- Q/U emission from instrument itself
  TECHNOLOGY: low-emissivity dielectrics (large & broad-band)

Polarization Systematics

- I → Q/U near on-axis: dipole, etc.
  TECHNOLOGY: big, telescope (pushes effects to high ℓ)

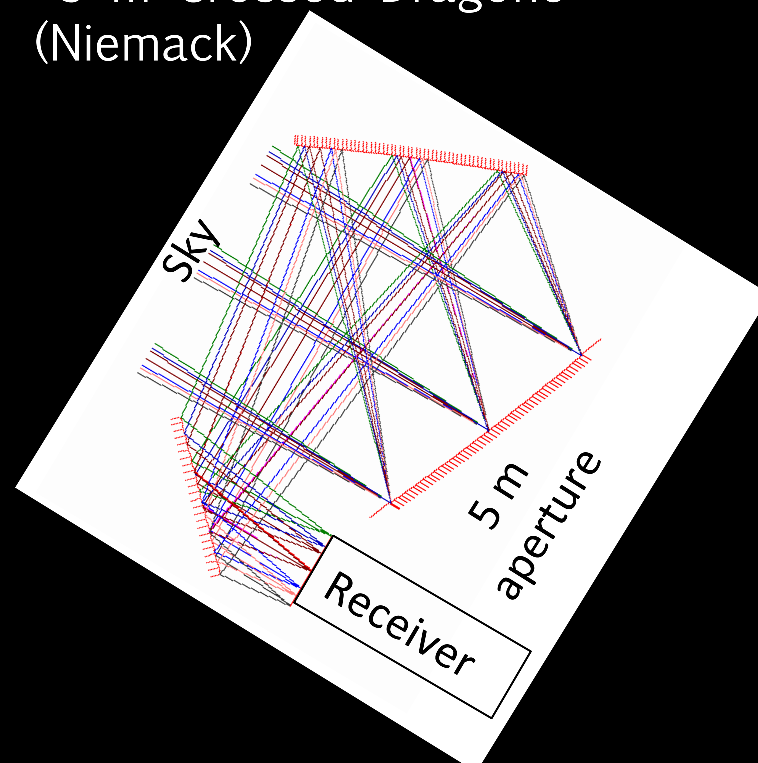
- I → Q/U far side-lobes.
  TECHNOLOGY: baffling



QUIET: 1.4 m Crossed Dragone with absorbing baffle (HEMTs)

Figure courtesy of O. Tajima

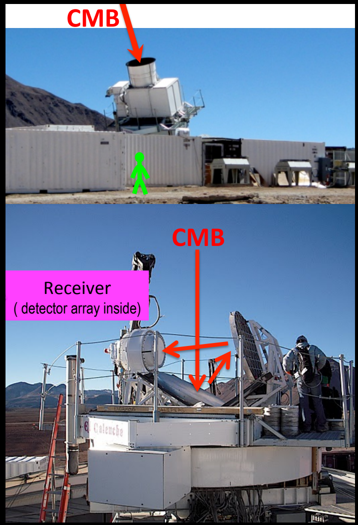
EXAMPLE PROPOSAL:
5 m Crossed Dragone (Niemack)



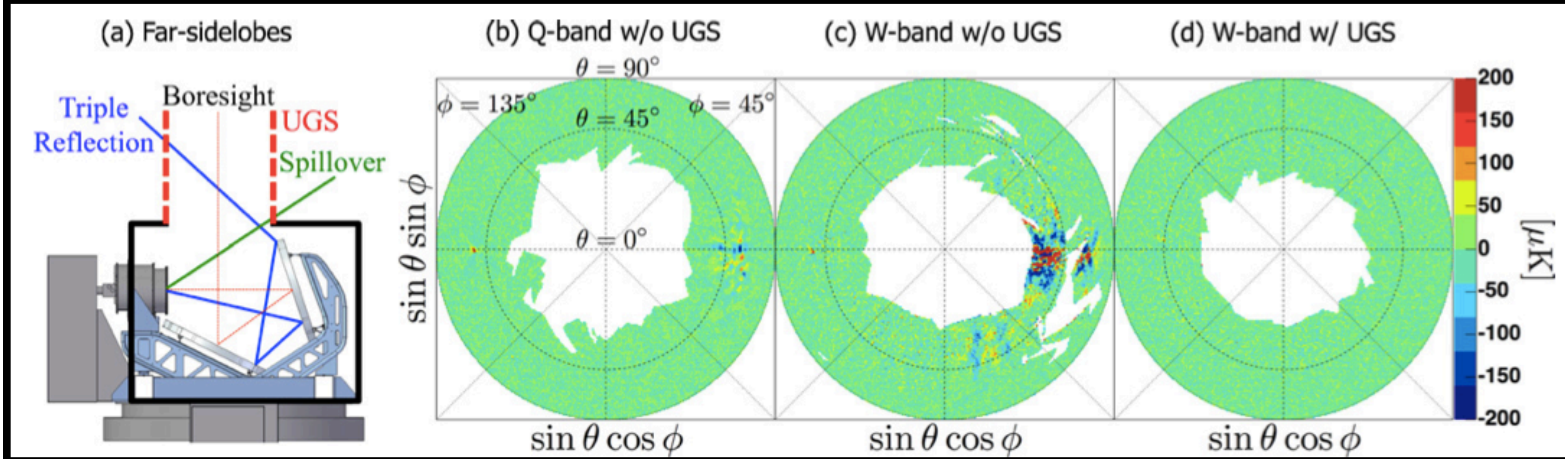
Polarization Systematics

- I → Q/U far side-lobes.
  TECHNOLOGY: baffling

5000 K Sun can be useful! QUIET had delays with its upper baffle construction and was able to map out how much it was needed.



QUIET:
1.4 m
Crossed
Dragone
with
absorbing
baffle
(HEMTs)



QUIET Collaboration et al, ApJ 768:9, 2013

Polarization Systematics

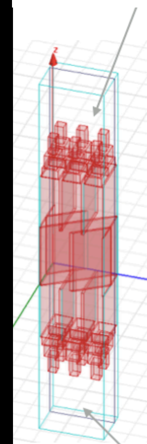
- I → Q/U on-axis,
  TECHNOLOGY: modulators

Also: large low-loss silicon metamaterial AR lenses & more.

- I → Q/U near on-axis: dipole, etc.
  TECHNOLOGY: lenses (large & broad-band)

- Q/U emission from instrument itself
  TECHNOLOGY: low-emissivity dielectrics (large & broad-band)

SILICON METAMATERIAL HWP
(J. McMahon)

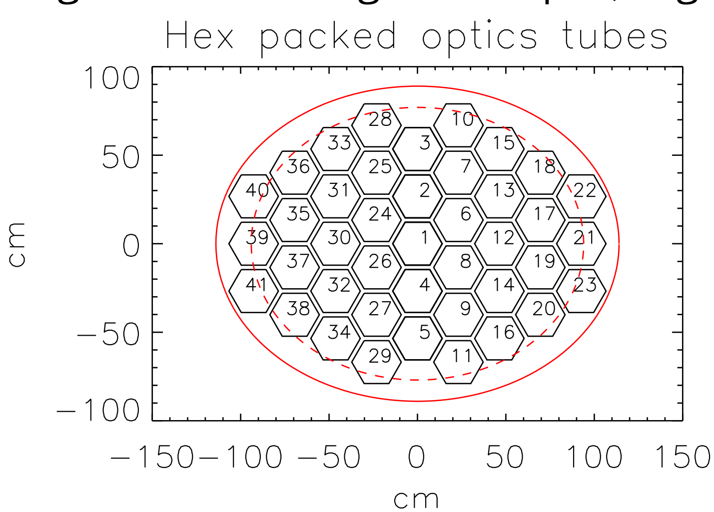


Concept: cut anisotropic structures into silicon to engineer a birefringent metamaterial

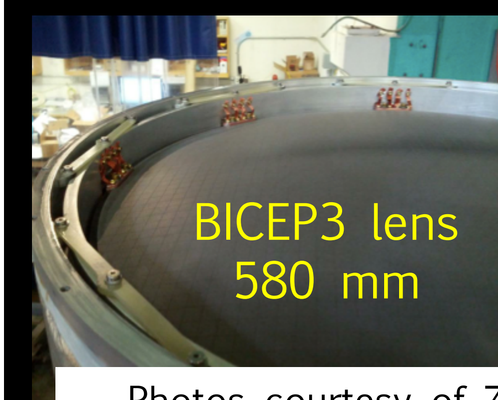
Advantages:
(1) larger birefringence than sapphire leads to thinner half wave plates with lower loss and emission
(2) easy to AR coat

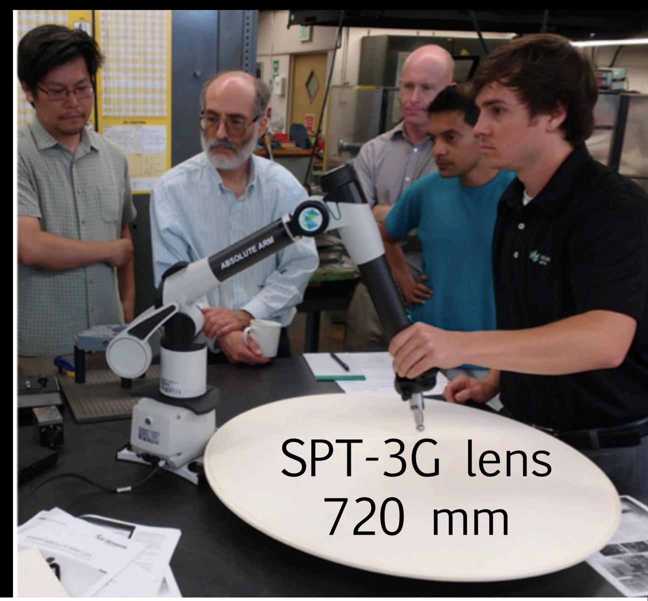
predicted performance:
- <1.5 K emission @ 300K
- > 95% modulation efficiency
- <2% reflections

Big lenses for big telescopes, e.g.



Huge AR-coated Alumina lenses





Photos courtesy of Z. Ahmed (Michigan S4 Workshop)

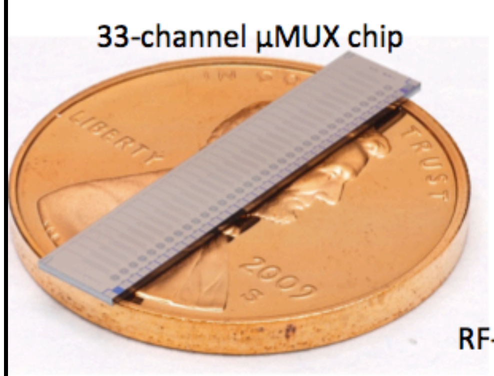
One More Technology

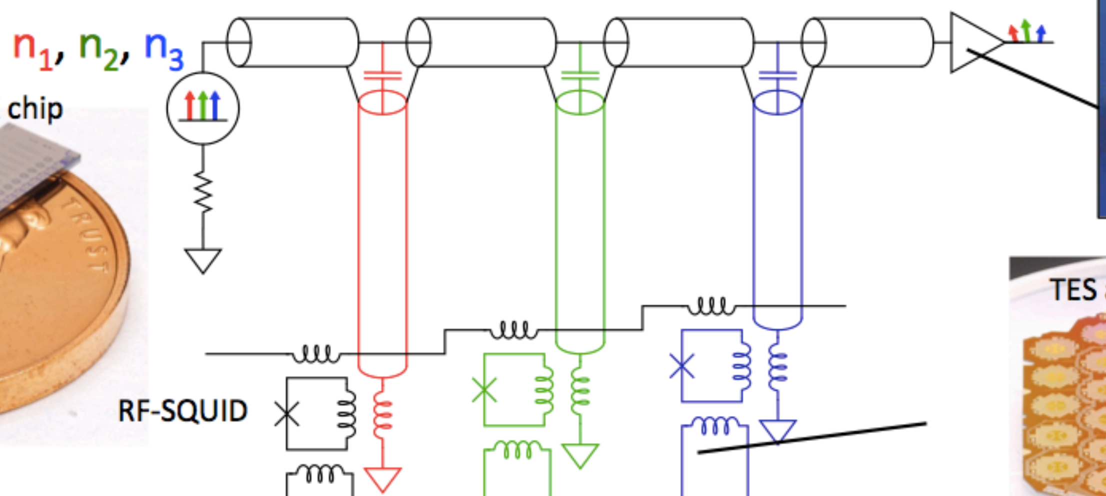
Standard CMB muxing methods now are expensive and space-consuming. Need improvements. KPUP is another.

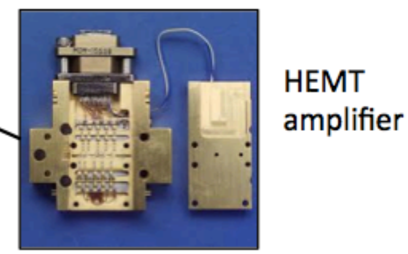
See J. Ullom talk tomorrow!

Microwave SQUID Multiplexing (µMUX)

- combines advantages of microwave resonator-based readout with advantages of TES sensors







- low noise: $I_N < 20\ \mathrm{pA}/\sqrt{\mathrm{Hz}}$
  - order of magnitude lower than expected photon noise for CMB-S4
  - no multiplexed disadvantage
- clear path to MKID-like multiplexing factors or significantly higher with hybrid multiplexing schemes (i.e. CDM or FDM within µwave SQUID)

Content detail courtesy of H. Hubmayr, NIST

Princeton Tritium Observatory for Light, Early-universe, Massive-neutrino Yield (PTOLEMY)
Goals for 2015: Tritium-loaded Graphene Surface from
0.15eV@100eV TES Energy Resolution fr
d/ANL
Integrated Graphene / TES into 1% MAC
Spectrum
New Forefront for Calorimeter-ba
ndpoint
BONUS SLIDE
courtesy of Chris Tully
SuperNova
Reactor
Accelerator
Terrestrial
Solar
Big Bang
PTOLEMY
PPPL
(May 2015)
1 mm
TES
1.09 Å
1.63 Å
3.2 T
18.4 kV
100 V
0 V
-90 V
-95 V
-99 V